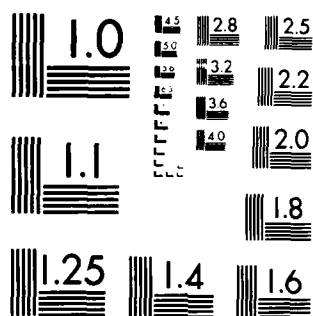


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EFFECTIVE DEVELOPMENT OF THE ADVANCED DIRECTIONAL SHEAR CELL
AT WATERWAYS EXPERIMENTAL STATION
FINAL TECHNICAL REPORT

by

J. Robin F. Arthur

April 1968

United States Army

WATERWAYS RESEARCH OFFICE OF THE U. S. ARMY

London, England

Contract No. DAA-37-0-0000

University College, London

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An advanced Directional Shear Cell has been set up at the Geotechnical Laboratory, Waterways Experiment Station, U.S. Army Corps of Engineers and a program of testing has been carried out there in order to introduce WES personnel to the equipment and carry on the development of the equipment in its working environment. Results of this program are reported and recommendations are made for the future successful use of the equipment at WES.					
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SUMMARY

An advanced Directional Shear Cell has been set up at the Geotechnical Division, Waterways Experimental Station, U.S. Corps of Engineers and a program of testing has been carried out there in order to introduce WES personnel to the equipment and carry on the development of the equipment in its working environment. Results of this program are reported and recommendations are made for the future successful use of the equipment at WES.

KEYWORDS

Plane Strain Shear Apparatus, Soil Anisotropy, Stress Path, Controlled Principal Stress Rotation

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INTRODUCTION

This report covers the full period of development of the advanced DSC at WES; during this period the UCL research assistant John Pulsford was seconded to WES and worked full time on the DSC in the Geotechnical Laboratory. The working environment proved very good and the equipment was set up and operating in six weeks. Given the nature of the equipment and the difficulty for John Pulsford in operating so far from back up UCL expertise the remaining stages of work on this contract were bound to be exceptionally demanding. Development of such state of the art equipment would inevitably have had some difficulties and set backs even on home base so it is not surprising that this report cannot be a catalogue of uninterrupted success. The work has indeed been successful in that the conditions for future successful operation of the DSC at WES have been defined. The work has also been fruitful in terms of apparatus development. There is no doubt that major contributions to research could be made by using this DSC at WES. In the opinion of the author there are two conditions to be met to achieve this success: these become clear in surveying the work carried out under this contract and will form the main conclusions.

The difficulties encountered at WES in the development period were largely due to lack of radiography and of equipment for reducing strain data. There was insufficient appreciation of the need for strain distribution measurements and direct interpretation of radiographs to assess the performance of both apparatus and experimental techniques. The need was increased by the small sample size which was chosen to ease sample handling and so that undistorted samples from the field could be tested. It is worth recalling that during the first stage of the preceding contract it was found at UCL by using radiography that acceptable uniformity of strains could not be obtained when the sample size was reduced to a 75mm cube so that the size adopted was 75mm.100mm.100mm. The thickness in the intermediate principal stress direction being reduced from 100mm to 75mm. Further difficulties were also to be expected in the development of a device operating at much higher stress levels than those used hitherto. In spite of this fore warning there was a clearly qualified hope that it would prove possible to use surface measurements to compute strains.

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The automatic shear sheet alignment system was designed to carry out this task although UCL warned throughout that this method might well fail. The fall back position was that photography should be used at WES at least until funds became available to set up radiography. In addition there did seem to be a possibility that a 100kV x-ray set could be available at WES immediately and John Pulsford carried out tests before leaving UCL for WES which showed that 100kV was sufficiently powerful to obtain satisfactory radiographs. These possibilities had been discussed at WES during a visit by the author to WES in June 1966 and the need for provision for measuring strain distributions obtained from either radiographs or photographs was also pointed out. In the report after the visit the author mentioned the mono-comparator system used at MIT for this purpose and indicated a ball park cost of \$10000. The necessity for this measurement system may not have been emphasised sufficiently and certainly WES had no funds for this.

- The significance of measuring strain distributions is not widely understood; those who do work in this way know that the uniformity of strain within a sample cannot be adequately measured without such data. It is frequently observed that samples with apparently uniform strains have in fact an unacceptable degree of non-uniformity. The need to have accurate information on the uniformity of strains is greatest when a really new and complex shear device is being put into service for the first time. These observations and reflections set the scene for the remainder of this report including the conclusions. It is hoped that these conclusions will be seen as offering a very positive and constructive solution to the problems which the report highlights. It would be sad if the conditions at WES could not be arranged so that the great potential of the new ISO could be exploited there. Previous ISOs with the same cross-section (100mm sq.) in the plane of strain have demonstrated great research potential (1 & 2) in an area where there is a concentration of research interest (3). It would be tragic if the possibility at WES to achieve cooperation between international research groups and to evaluate impartially the most complex and promising shear apparatuses was not realised.

AN OVER VIEW OF THE PROGRAM

In the proposal the purposes of the program were set out as follows:

1. to train WES personnel in all aspects of DSC testing,
2. to explore and extend the capabilities of the new DSC,
3. to carry out true research using the unique capabilities of the new DSC,
4. to train WES personnel to make shear sheets and pressure bags.

In addition there was a firm intention to carry out undrained shear tests on sands and if possible on clays.

All these aims except for 2 were achieved at varying levels but progress was slower than anticipated and in retrospect it is easy to attribute this to the inability of WES to assign a person to work with John Pulsford full time, the lack of X-rays and critically the lack of emphasis on evaluating incremental strain distribution test by test. Around 12 months after the contract got underway and during a visit by the chief investigator a mechanical system for recording strain photographs was organized and its failure for measuring the overall incremental strains were borrowed at UCL. Unfortunately this system was not used subsequently for measuring strain distributions test by test, and indeed it may have been impossible to achieve in the local circumstances. This has meant that the evaluation of success or failure of a test had to wait until strain distributions were measured at the end of the whole testing program at UCL. On the basis of normal UCL criteria very few of these tests can be judged successful. Many of the tests appeared to have had non-uniform plane strain end lubrication; there was no way that John Pulsford could have diagnosed this at the time without the strain distribution data. The main indicator for poor end lubrication is non-uniform strain distribution, but strongly abnormal stress-strain curves and unexpectedly high shear resistance are other indicators. Achieving sufficient lubrication on the ends without lowering the quality of the photography is difficult; grease thickness and the time that the sample is left under isotropic stress needs careful regulation. The best way out of this problem is to use radiography.

A considerable number of other tests ended in premature failure due to breakdown of the normal WCL glass sand layer for shear transfer on the inside of the sample membrane. This appears to have been due to the raised stress level at which the new DSI operates and it is clear that a modification is needed. John Pulsford did eventually manage to diagnose this fault by careful examination of what remained of the sample membranes after the somewhat damaging process of dismantling the apparatus post testing. Incremental radiographs during testing would have revealed this problem immediately through a darkening of the thin zones on the radiographic image of the sample boundary. The process is sudden and probably does not show up on strain distributions, but Coulomb failure planes are another symptom. Without radiographs much time was lost devising tests to explain the behaviour this fault caused.

The work could be regarded as very acceptably successful as an apparatus development period. Considerable numbers of modifications were made which improved overall performance but it should be emphasised that this process would not have allowed the test programme to result in a large number of successful tests.

The Table of Test Program Details has briefly described the tests carried out. In this area tests that can be considered successful on normal WCL criteria are summarised. Figure 1 defines a 'good' test which are given in the table. The abbreviations 'b' and 's' stand for failures of boundary lubrication and shear transfer respectively. Bag inflation indicates a change in shape of the normal pressure bag in which one end of the bag expands and the other contracts correspondingly; it is likely to result in a non uniform application of normal stress and is caused by a bag to backing plate gelling failure.

The success rate of 100% 5 tests in 41 is low and the reasons for this have already been suggested. It should be contrasted with the 38% success rate achieved at the same criteria in the initial period of development at WCL. 8 tests in 21. These successful tests at WCL included three real research tests, one of them involving uni-directional continuous rotation of the principal stresses in excess of 160°. This is no more than an indication of the effects of experience backed by radiography and regular strain distribution measurement.

During the period of this work a BSC of inferior design, but with same alloy chain shear sheet system, has been in use at UCL. Many successful tests have been carried out at the low stress level of $\sigma = 14\text{kPa}$, with no sign of restriction due to the shear sheets, there are clearly no grounds for attributing the problems at low stress level to the design, but there is a requirement to improve the method of shear transfer to the sample from the inside of the sample membrane when $\sigma > 30\text{kPa}$ for dense sand and $\sigma > 60\text{kPa}$ for loose sand. It is not considered that this will present serious difficulties. Until this problem is solved the stress level limits indicated above should be used. The effects of insufficient plane strain and lubrication are undoubtedly underestimated in the Table of results; this comment is based on work done at UCL over the same period. The comparison of photographic and radiographic means of determining strain distributions reported by Wong and Arthur (1985) was achieved on a well developed apparatus with the back up of radiographic observation always at hand. This work involved a careful balancing of the conflicting requirements of plane strain and lubrication and clarity of photographic image. Both the camera and the transducer recording device were well suited to the purpose. A well established radiographic procedure a slight modification of which was the achievement of some successful tests.

PRESENTATION OF DATA

Presentation of data in this report will be limited to illustrating points of interest directly related to the contract; all experimental data have been resampled to WEB. These include complete photocopies of John Foleford's experimental note books with further test by test annotations explaining the outcome of each. The complete computer output of all the strain distribution measurements which were made subsequently at UCL are also included.

It is appropriate to start by illustrating the use of strain distributions to discriminate between tests. The areas over which the distributions are measured are shown in Figure 2. In Figures 3 and 4 the stress-strain data of Tests J and K are plotted using the average strain

for each of the areas shown in Figure 2. Ideally the strains measured in the three areas at any given stress ratio σ/σ_c should be equal because the samples were prepared to be entirely homogeneous. In Test Q there is diminishing strain towards the edges of the sample suggesting poor boundary stress distribution or lubrication; this variation is unacceptably high and one notes that the deficiency would not have been discovered by boundary strain measurements or any four point measurement process. In Test X strains for the three areas are acceptably similar and the test is successful until the disintegration of the glued sand layer on the inside of the sample membrane stops boundary shear transfer and causes premature failure of the whole sample.

In contrast to the premature failure of Test X which was carried out at $\sigma_c = 60$ kPa Figure 5 shows the results of Test A1 carried out at $\sigma_c = 30$ kPa here the test was completely successful with the maximum shear stress applied through the boundaries and the averages of the strain distribution in areas 1 and 2 (see Figure 1) very close. Unfortunately it was not sufficient to then move to lower the stress level to ensure success; the three stage tests A1 and A4 both appear to show the effects of an ill test plane stress and lubrication although in rather different ways; see the are given in Figures 6 and 7. In Figure 6 the last two increments of loading in the first stage of A1 show a remarkable increase in stiffness which seems likely to indicate severe failure of the plane stress and lubrication and this is confirmed in the uncharacteristic stiffness after a 90° rotation of principal stress directions in the second stage - compare with 3rd stage of Test X in Figure 4 (c). In Figure 7 Test A4 shows less severe effects of end lubrication failure but nevertheless the inhomogeneity of the strain distribution is quite unacceptable. Figure 8 shows Test A14 in which the homogeneity of the strain distributions is perhaps just acceptable; this is an encouraging result in that the minor principal stress is high at 60kPa, maximum boundary shear stress was applied and the sample was saturated. This result was achieved after a number of failures of gluing techniques under saturated conditions but it must be noted that this was a loose sand sample there is still a general shear transfer problem to be solved. Work on this is being initiated at UCL now; it is not thought to be a serious long term problem.

It should also be mentioned that undrained tests on clay are in progress at UCL; these are computer controlled to keep the pore water pressure zero; there are two pore water pressure probes in each sample.

Test V is especially interesting as it includes a series of approximate strain distribution measurements made at WES which can be compared with subsequent distribution measurements at UCL. Figure 9a shows the successive series of four point measurements made at WES and Figure 9b shows that all the four point measurements except those based on the four points nearest the corners lead to something close to passable stress-strain curves. Figure 9c shows the subsequent UCL determination for area 2 (Figure 2) superimposed on the WES data points; there is clearly an acceptable fit. The UCL data for this test allows comparison of the coefficient of variation for ϵ_v with that for a UCL test determination reported by Wong and Arthur (4) (shown here as Fig 9d); the respective coefficients are 1.04 and 1.22. This suggests that the lubrication, photography and measurement techniques achieved at WES were on occasion adequate at the higher stress level of $\sigma_v = 60 \text{ kPa}$, and it should be recognized that photographic determination are always inferior to those from ring shear. For instance for the two samples, distortion was 10% and stress was 10% (the coefficient of variation is 1.1). Figure 9e is a collection of four rather large improvement photographs providing a comparison of strain in three or all planes of strain throughout the samples; it is this repeatability that allows performance defects such as the failure of the shear test at $\sigma_v = 10 \text{ kPa}$ to be reported immediately (5). In the context of this past program the strain distribution determined for this test was a serious distortion in that it gave a quite false reassurance about the uniformity of these strain distributions in other tests in the program. Test V was the only test for which a strain distribution was calculated during the program; at WES all the others were calculated subsequently at UCL; this test was one of the 11% successes in the program.

APPARATUS DEVELOPMENT

As one would expect a number of important improvements were made over the period and observations were made which will lead to further improvements. The original roller guides for the shear sheets were replaced by a new set sent from UCL and large modifications were made to the shear sheet guides. On the whole these guides have performed quite well but after considerable thought and effort it seems unlikely that the guides can be used as part of a boundary strain measurement system. This shifts the future effort to choosing a strain measuring system for the long term; the advantages of high definition radiography have been indicated in the previous paragraph. For the present a viable strain measuring system which is based on photography has been achieved; this system appears to provide a potential for measuring strain distributions which are essential to estimate the quality of particular tests. The low success rate of the test series indicates how necessary this is. A new technique of applying a brittle coating to the plane strain ends of the sample membrane allows at least the approximate orientation of rupture layers to be recorded but remains a poor substitute for radiography. In drained tests on saturated samples volume change has been measured in terms of water flow in or out of the sample again in view of some small edge effects causing variations in strain distribution within the sample this technique should be checked against radiographic strain distributions.

Effects of working at higher stress levels can be expected to be continue to be noticed for a considerable further period. So far the biggest improvement has been using an impact adhesive coating on the sample membrane to improve the bond between the shear sleeve and the membrane without making the bond permanent. It has been found that improved shear transfer from the inside of the sample membrane to the sample itself is the only pressing current need. This is the subject of a development program at UCL.

Improved uniformity of normal stress transfer from the pressure bag through the shear sheets has been achieved by inserting a silicon rubber

moulded pad between the two, this is shaped to compensate for the variations in thickness of the shear sheets.

CONCLUSIONS

Progress made during the contract was adequate rather than spectacular. Measurements of incremental strain distributions test by test would have provided the quality control to identify problems quickly and avoid repeating the same errors. This technique would have worked much the best with radiography which would have shown the frequent failures of boundary traction immediately (the advantage of radiography is in "seeing" every plane of strain simultaneously so very small local changes in density which occur consistently through the sample show up). The results of Test U gave a false sense of security on strain uniformity. Subsequent computations of strain distributions at UCL revealed the problems that have been discussed or are listed in the Table of Tests. The differences are due to several factors, the use of quality control by measuring incremental strain distributions test by test from radiograph is considered to be by far the most important. A disturbing realization comes from carrying out tests with this form of quality control: without this control many tests would appear to have uniform strain when in fact the strains were unacceptably non-uniform.

It was especially unfortunate that WES was unable to assign a person to this project full time. This reflects both the personal experience of the author and observation of other research groups which run sophisticated shear testing equipment. Expertise takes time to build up and it has to be developed by continual hands on experience; the lengths that the Imperial College go to to keep a talented person working on their hollow cylinder with a continuity overlap of six months when a new person is trained in the current skills comes to mind. UCL, and no doubt UCS, strive for the same with their BSC apparatuses. The successful transfer of BSC expertise to MIT from UCL was only possible because a talented research student worked full time on the BSC during nine months of the author's visit there and subsequently MIT arranged overlaps in time from good student to good

student. WES needs a talented and well motivated person to work for at least three years full time on the new DSC. Unless this condition is met it seems extremely likely that the money and intellectual effort that WES has invested will be wasted. The UCL group is willing to help in any way it can: some one from WES would be welcome to come to UCL for an initiation period. Perhaps a student registered for a higher degree at either UCB or MIT might be assigned for the major part of his or her postgraduate training: even registration with London University is a possibility that could be investigated. In addition to this WES is perhaps in the best position to bring together the four groups working with the DSC to pool their know how and talk through their differences. If a trial meeting of this group proved useful no doubt we would find ways to make the meeting regular events.

REFERENCES

1. Wong, S.K.B. and Arthur, J.S.P. 1968. Sand theories with linear variations in direction. *Geotechnique* 18, 1, 13-22.
2. Wong, S.K.B., Arthur, J.S.P. and Johnston, J. 1969. Soil as an isotropic linear elastic material and an elastoplastic material. *Intern. Eng. Sci.* 7, 4, 747-771.
3. Terzaghi, K. 1943. *Soil Mechanics*. J.T. and J.C. Int'l. A. 1948. *Soil Mechanics in Engineering*. Int'l. Laboratory Testing of Soils. *Intern. J. Civ. Engrg. Soil Mech. & Fdn. Eng.* Vol. 1, 57-159.
4. Wong, S.K.B. and Arthur, J.S.P. 1968. Determinations and assumed strain distributions in sand samples. *A.S.T.M. Geotech.* 1, 3, 341-357.
5. Arthur, J.S.P. 1970. Industrial Radiography in Soil Mechanics. *Brit. J. Non-destruct. Testing*, Jan. 77, 9-13.

TABLE OF TESTS

Month	Constant	Stage 1	Stage 2	Stage 3	Unsuccessful
#	Stress	$\psi^\circ; \phi^\circ_f; \phi^\circ_m$	$\Delta\psi^\circ; \phi^\circ_f; \phi^\circ_m$	$\Delta\psi^\circ; \phi^\circ_f; \phi^\circ_m$	lub; sh. tr; other
Sand	$\sigma_3; p$				
Apr.					
1	30kPa;	0°; ;49°			; ; boundary strain
Dense					technique fails
yel. LB					
A	35kPa;	0°; ;52°			as above
Dense					
Silver					
B	40kPa;	0°; ;48°	30°; ?;		as above
Dense					
P. Gil.					
C	20kPa;	0°; 47°;			as above
Dense					
UCL. LB (and all subsequent tests)					
May					
D	30kPa;	0°; ;46°			as above
Dense					
E	60kPa;	0°; ;30°	-20°; ; 30° etc		as above
Dense					

Month	Constant	Stage 1	Stage 2	Stage 3	Unsuccessful
#	Stress	$\psi^* ; \sigma'_f ; \rho'_m$	$\Delta\psi^* ; \sigma'_f ; \rho'_m$	$\Delta\psi^* ; \sigma'_f ; \rho'_m$	lub; sh. tr; other
Sand	$\sigma^3 ; p$				
June					
F	; 100kPa	45°; ; 49°			as above (<u>camera</u> <u>installed</u>)
Dense					
G	; 100kPa	45°; ; 41°			; ✓ ;
Dense					
H	; 100kPa	45°; ; 47°;			poor photos
Dense					
I	14/30kPa	0°; ; 46°	70°; 49°;		; ; poor photos
Dense					
J	60kPa;	45°; ; 41°			; ✓ ;
Dense					
July					
K	60kPa;	0°; ; 46°			poor photos
Dense					
L	60kPa;	45°; 41°;			
Loose					
M	100kPa;	0°; 41°;			poor photos
Loose					
N	60kPa;	0°; ; 41°	70°; 41°;		; ✓ ;

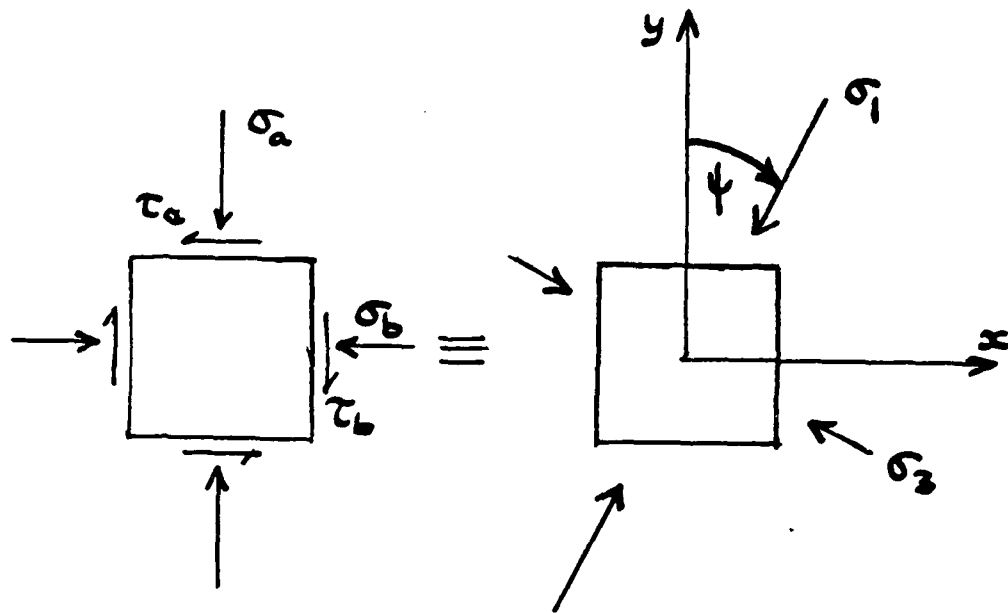
Month	Constant	Stage 1	Stage 2	Stage 3	Unsuccessful
#	Stress	ψ^* ; ϕ^* ; ϕ'^m	$\Delta\psi^*$; ϕ^* ; ϕ'^m	$\Delta\psi^*$; ϕ^* ; ϕ'^m	lub; sh. tr; other
Sand	σ^3 ; p				
Dense					
O	60kPa;	0°; ;41°	90°; ;41°		; ✓ ; bag instab.
Dense					
P	60kPa;	0°; ;46°	70°; 41°;		; ✓ ;
Dense					
Aug					
Q	60kPa;	0°; ;46°	90°; 48°;		✓ ; ;
Dense					
R	60kPa;	0°; ;41°	90°; ;46°-47°		?
Dense					
S	60kPa;	45°; 41°;			; ✓ ;
Dense					
T	60kPa;	45°; <46°;			; ✓ ;
Dense					
U	60kPa;	0°; 48°;			
Dense					
V	60kPa;	0°; ;46°	90°; ;46°	-90°; 48°;	✓ ; ;
Dense					

Month	Constant	Stage 1	Stage 2	Stage 3	Unsuccessful
#	Stress	ψ^* ; ϕ^* ; ϕ^*m	$\Delta\psi^*$; ϕ^* ; ϕ^*m	$\Delta\psi^*$; ϕ^* ; ϕ^*m	lub; sh. tr; other
Sand	σ^3 ; p				
Sept					
W	60kPa;	45°; 41°			; ; p. bag failing
Dense					
X	<u>60kPa;</u>	<u>0°; ; 46°</u>	70°; 45°;		; ✓ ;
Dense					
Y	60kPa;	45°; 43°;			; ✓ ;
Dense					
Z	60kPa;	0°; ?;			✓ ; ;
Dense					
A1	30kPa;	45°; 47°			; ✓ ;
Dense					
A2	<u>30kPa;</u>	<u>45°; 49°;</u>			
Dense					
Oct					
A3	30kPa;	0°; ; 41°	70°; ; 41°	-70°; 52°;	✓ ; ;
Dense					
A4	30kPa;	0°; ; 41°	90°; ; 41°	-90°; 52°;	✓ ; ;

Month	Constant	Stage 1	Stage 2	Stage 3	Unsuccessful
#	Stress	$\psi^0; \phi^1; \phi^1_m$	$\Delta\psi^0; \phi^1; \phi^1_m$	$\Delta\psi^0; \phi^1; \phi^1_m$	lub; sh. tr; other
Sand	$\sigma^3; p$				
Dense					
A5	30kPa	0°; ;40°	20°; ;40	etc	; ;sh.sheet &p.bag interference
Dense					
A6	60kPa	45°;45°;			; ✓ ;
Dense					
A7	?kPa	0°; ;40°	20°; ;40°	etc	; ✓ ; saturated sample
Dense					
A8	?kPa	0°;44°;			; ✓ ; "
Dense					
A9	30kPa	0°;43°;			; ✓ ; "
Dense					
Nov					
A10	?kPa	45°;45°;			; ✓ ;
Dense					
All	omitted				
A12	?kPa	45°;46°;			; ✓ ; saturated sample
Dense					

LIST OF FIGURES

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2. Areas of strain distribution computed at UCL.
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4. Stress strain data for Test X.
5. Stress strain data for Test A2.
6. Stress strain data for Test A3.
7. Stress strain data for Test A4.
8. Stress strain data for Test A14.
9. Stress strain data for Test U.



$$p = \frac{(\sigma_a + \sigma_b)}{2} = \frac{(\sigma_1 + \sigma_3)}{2}$$

$$\phi'_f = \sin^{-1} \left[\frac{(\sigma_1/\sigma_3)_{\max} - 1}{(\sigma_1/\sigma_3)_{\max} + 1} \right]$$

f = failure

$$\phi'_m = \sin^{-1} \left[\frac{(\sigma_1/\sigma_3) - 1}{(\sigma_1/\sigma_3) + 1} \right]$$

m = mobilised

Figure 1

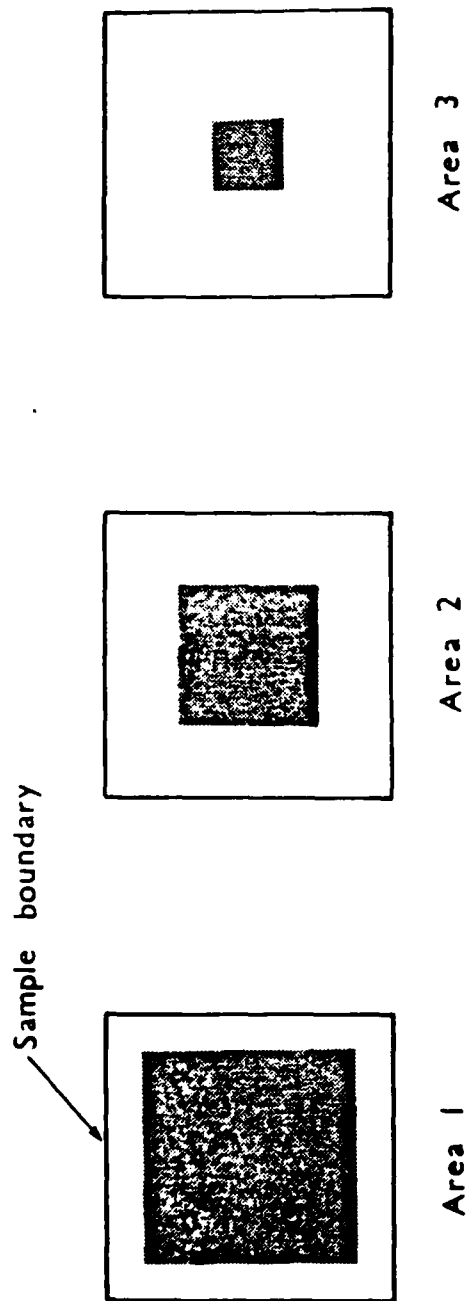


Figure 2

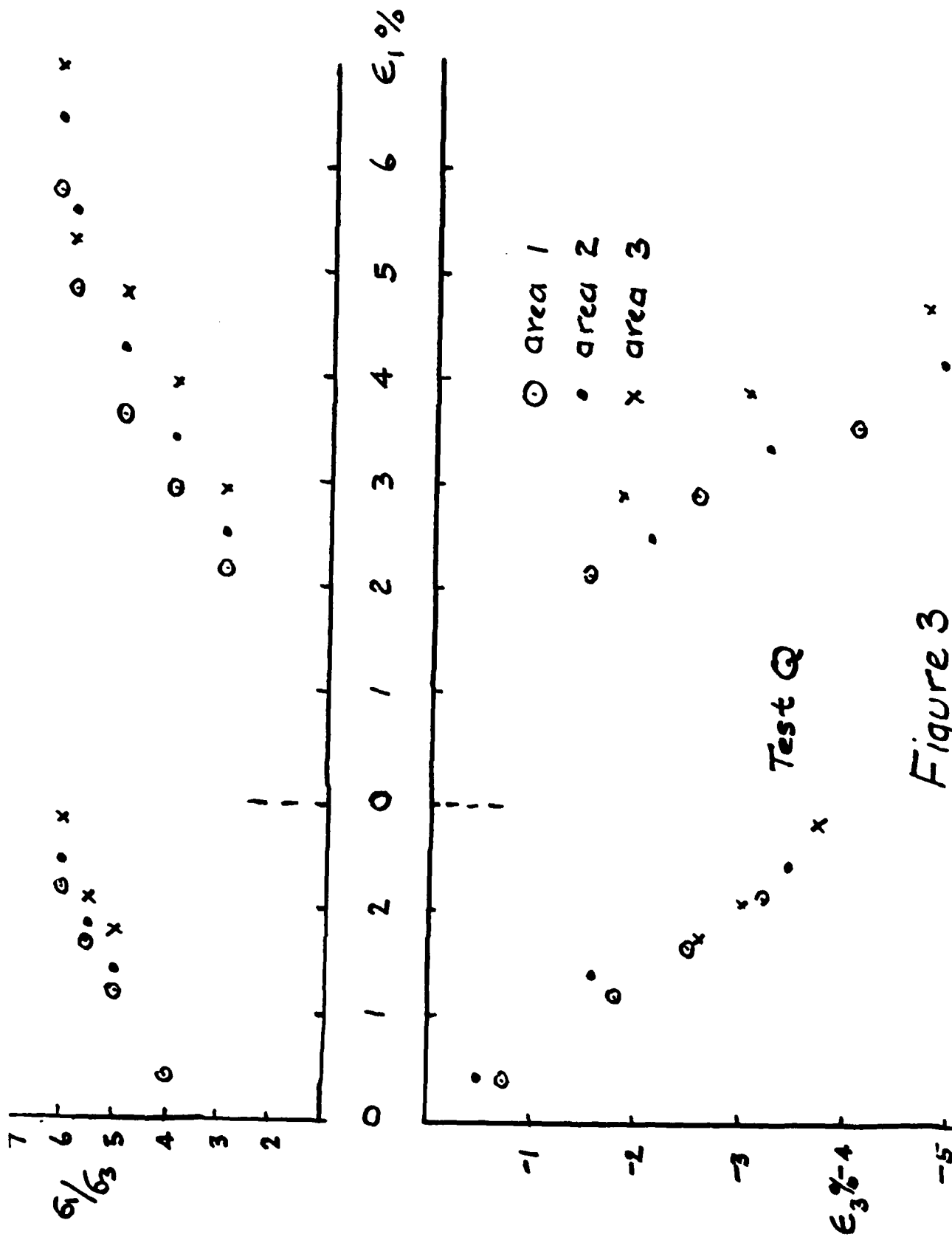


Figure 3

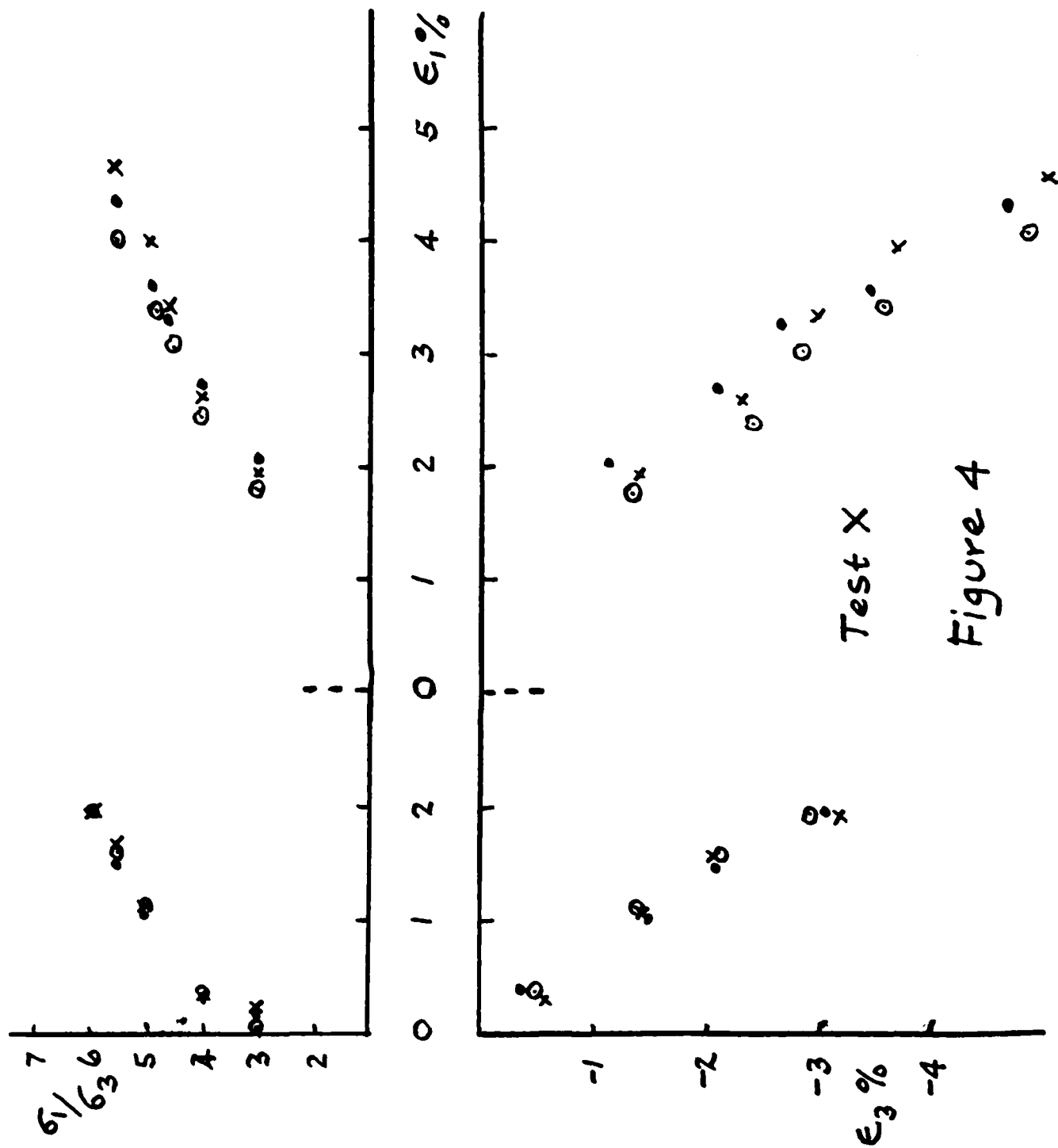
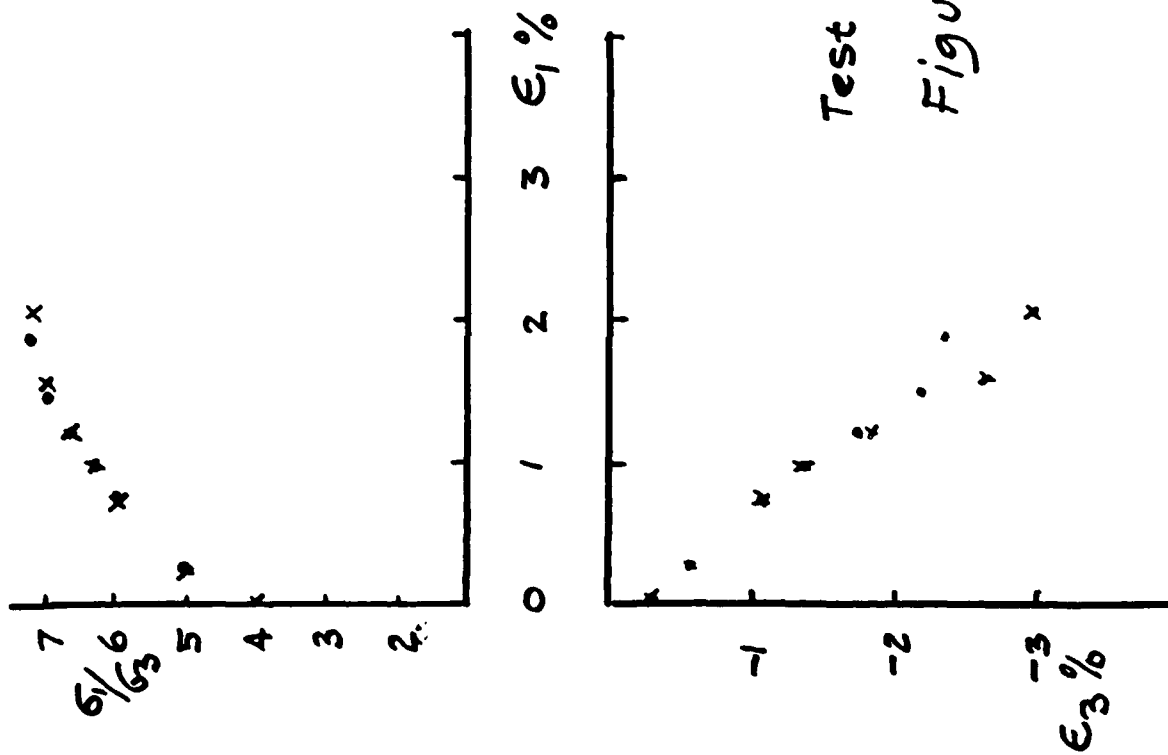
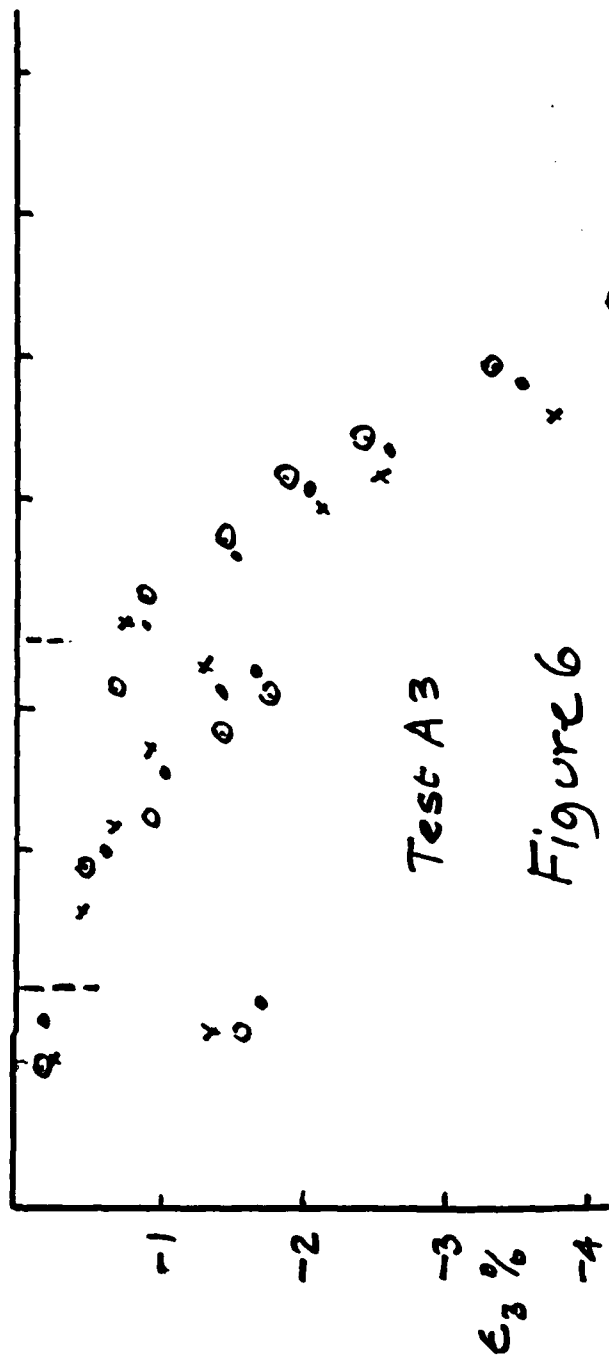
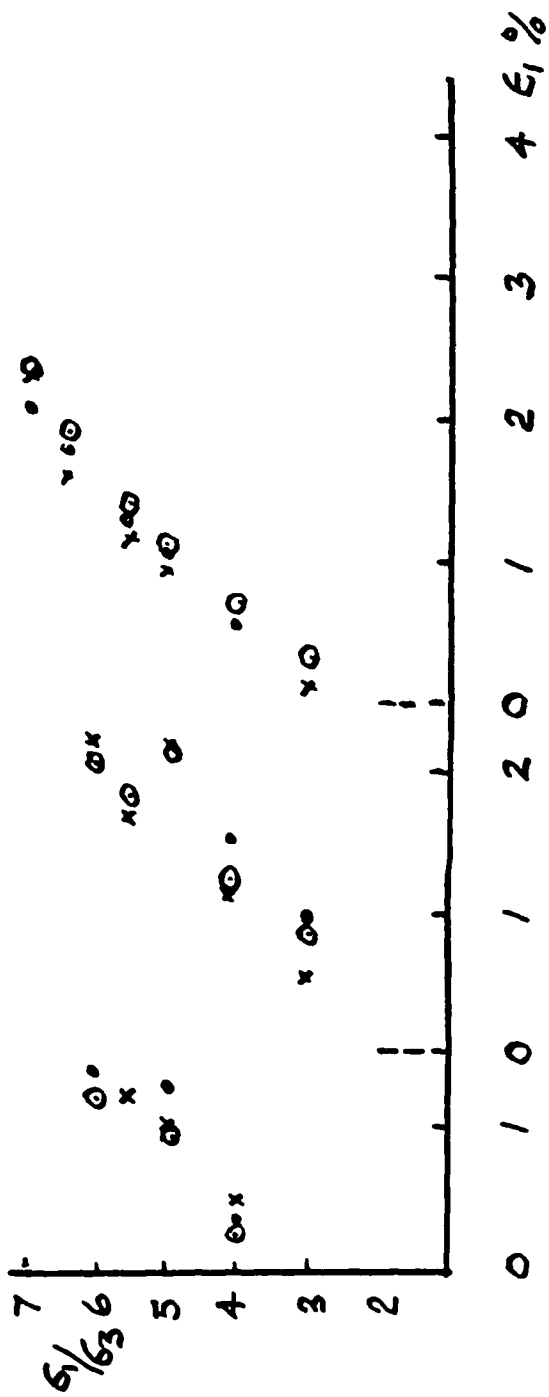


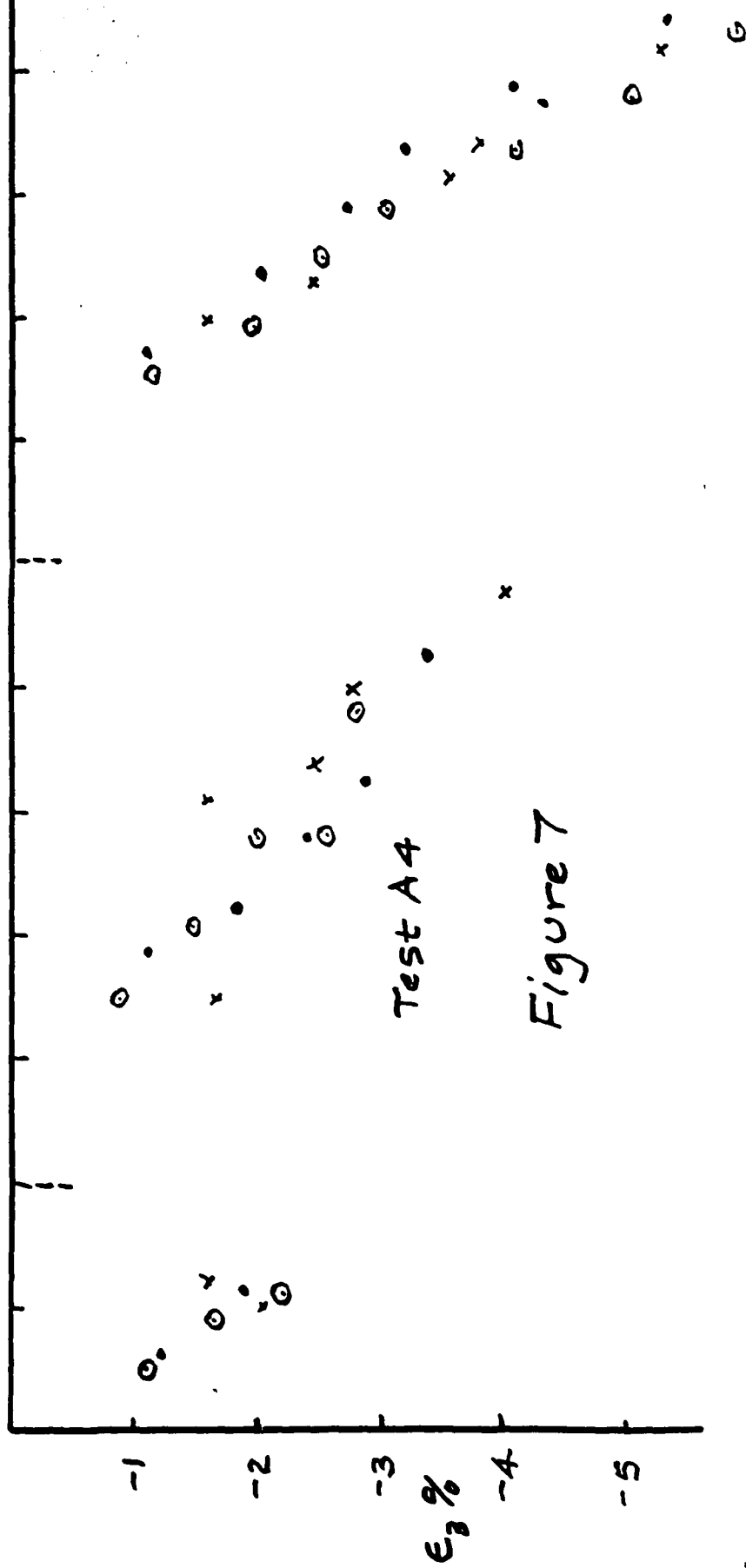
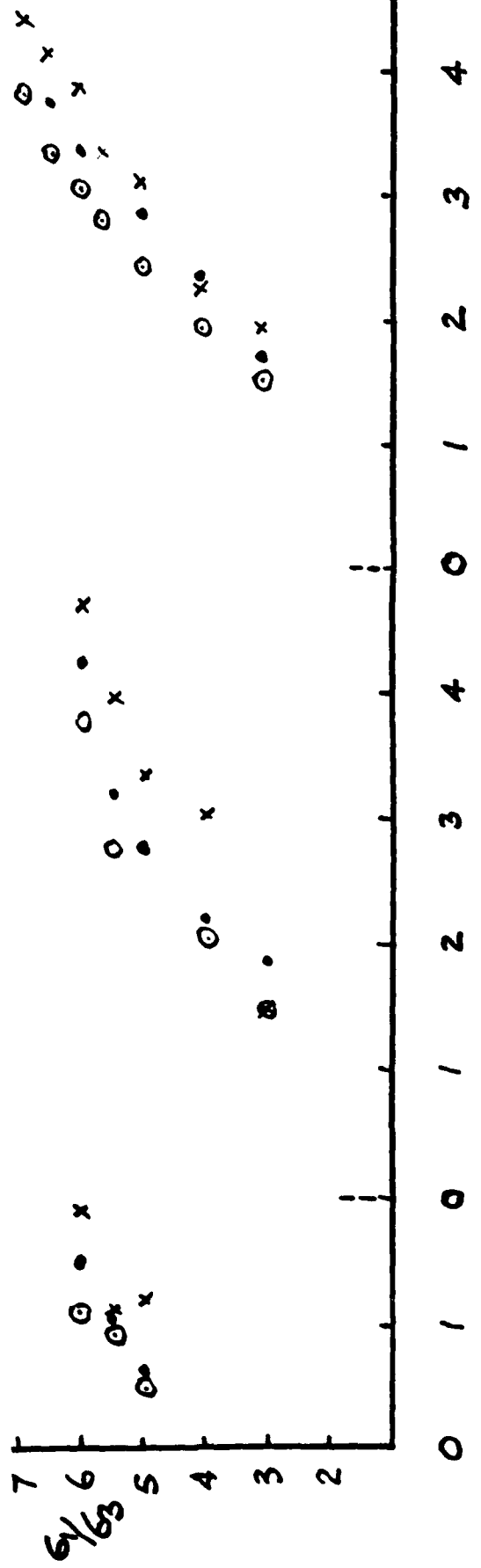
Figure 4





Test A3

Figure 6



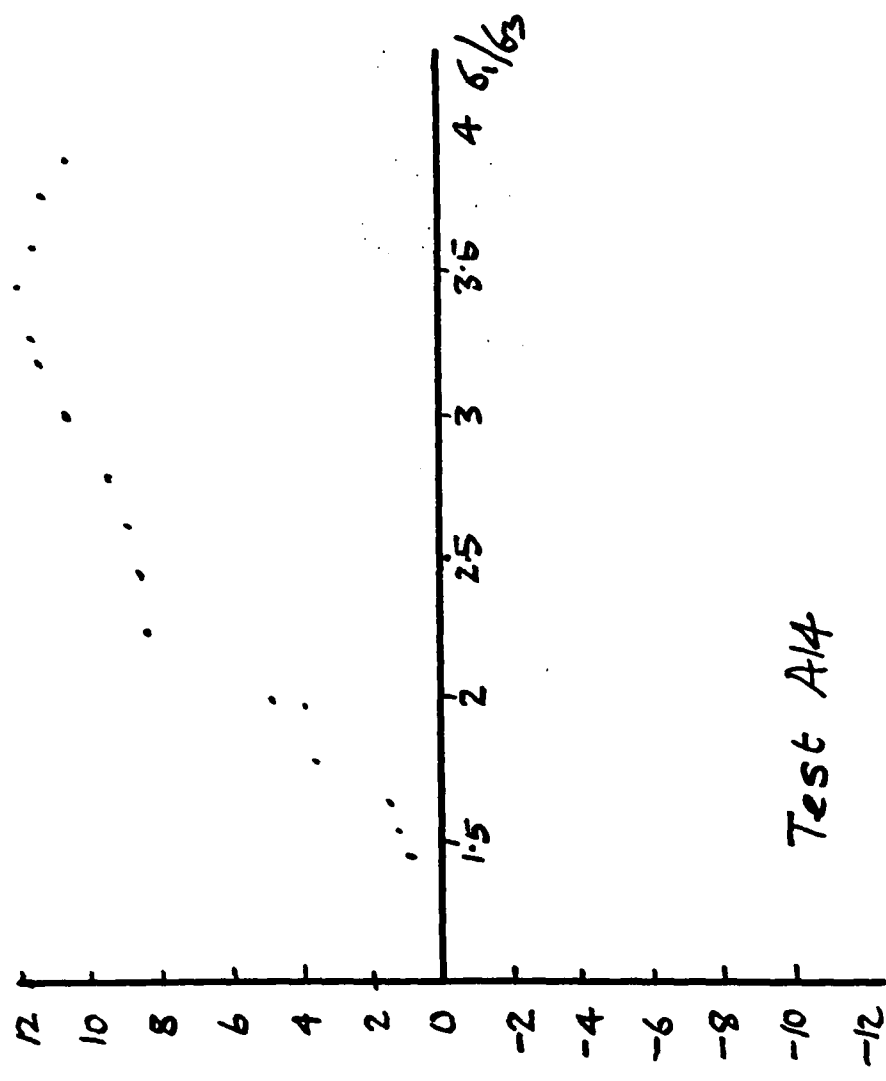
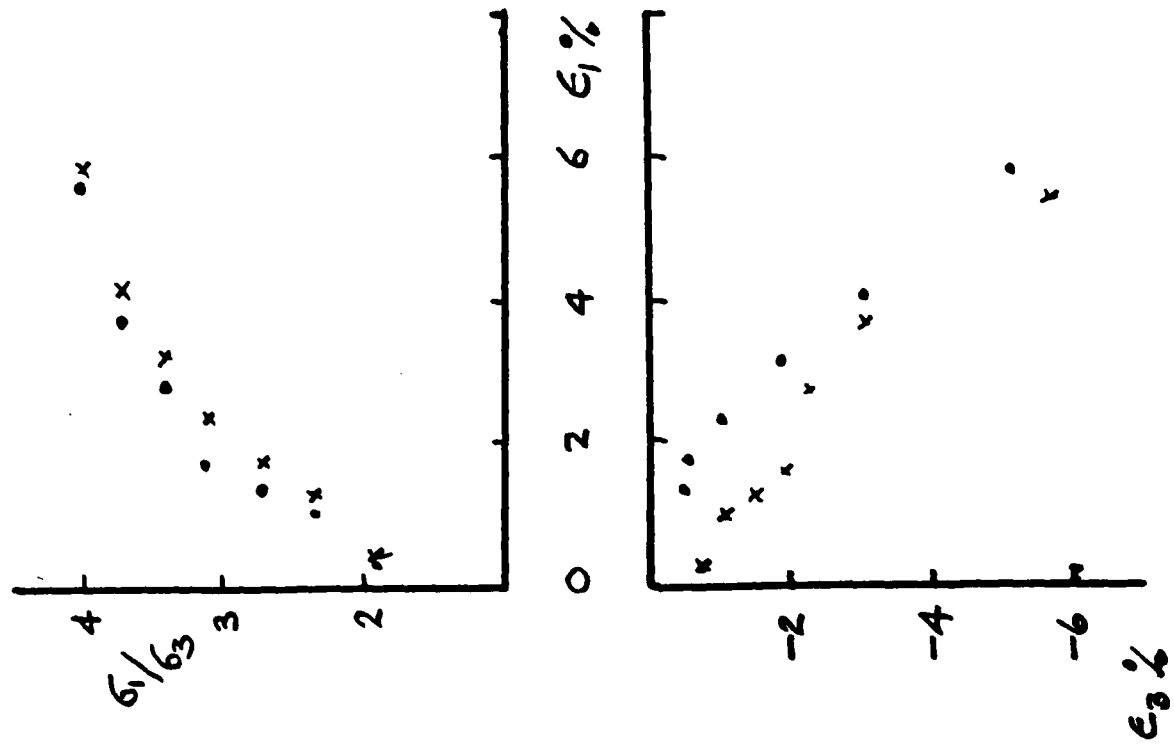
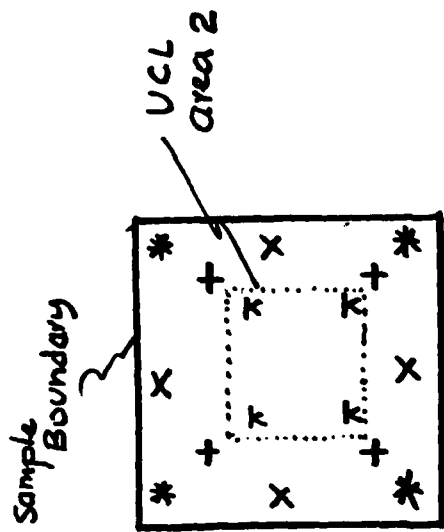
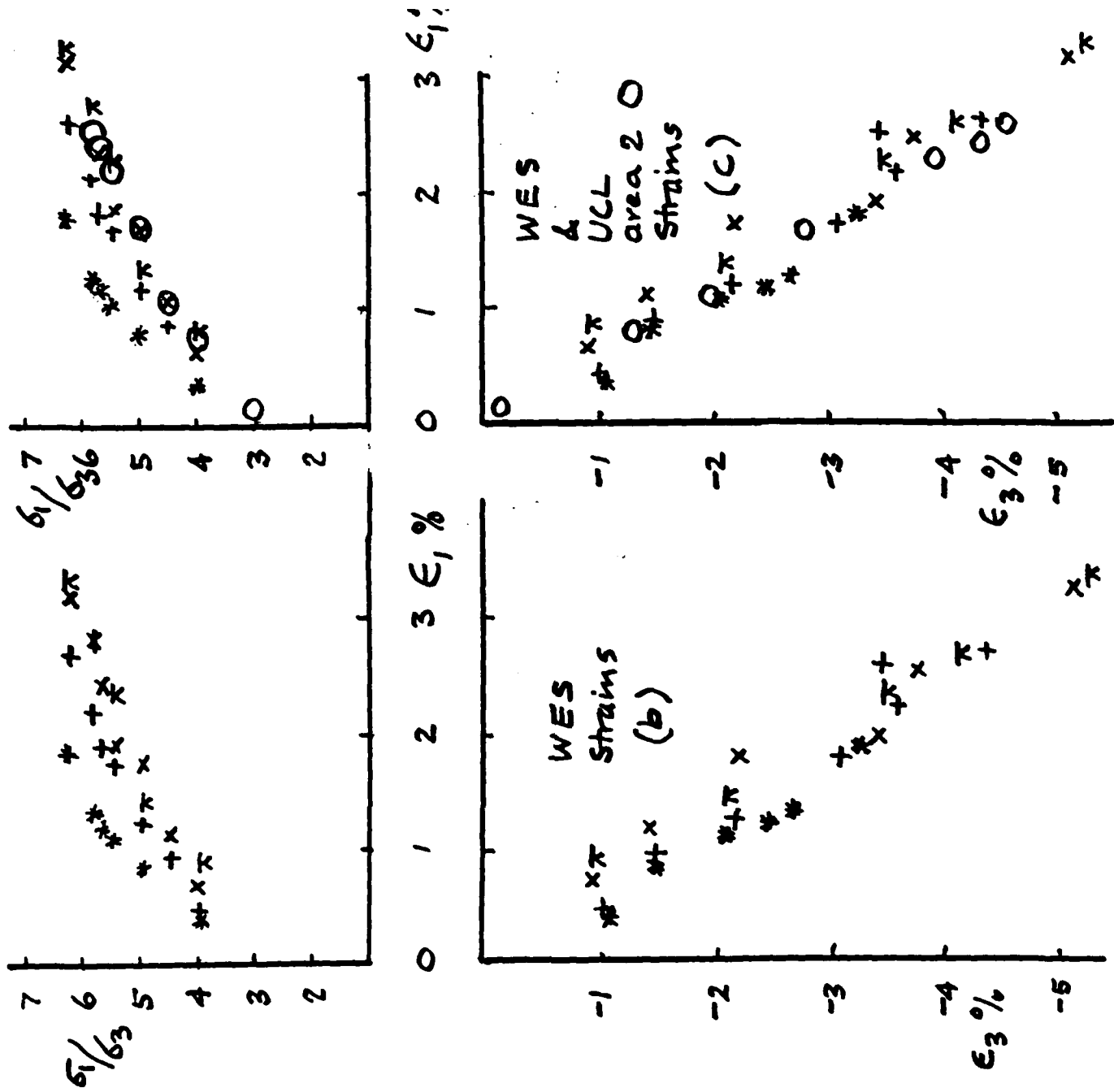


Figure 8



* 90 x 90 mm "square"
 x 90 x 90 mm "diagonal"
 + 60 x 60 mm
 π 40 x 40 mm

WES measuring points

(a)

Figure 9(a to c)

σ_1

1.03	2.48	1.92	1.10	1.74	0.73	
1.25	1.89	2.00	1.30	1.68	0.09	
0.38	1.06	2.17	1.70	1.30	0.42	
0.17	1.51	2.39	1.72	1.30	1.78	
1.37	2.20	1.73	1.74	1.66	1.26	
1.12	1.38	1.90	2.33	0.96	1.80	

Average ϵ_1 (area 1) = 1.46% with standard deviation 0.60%

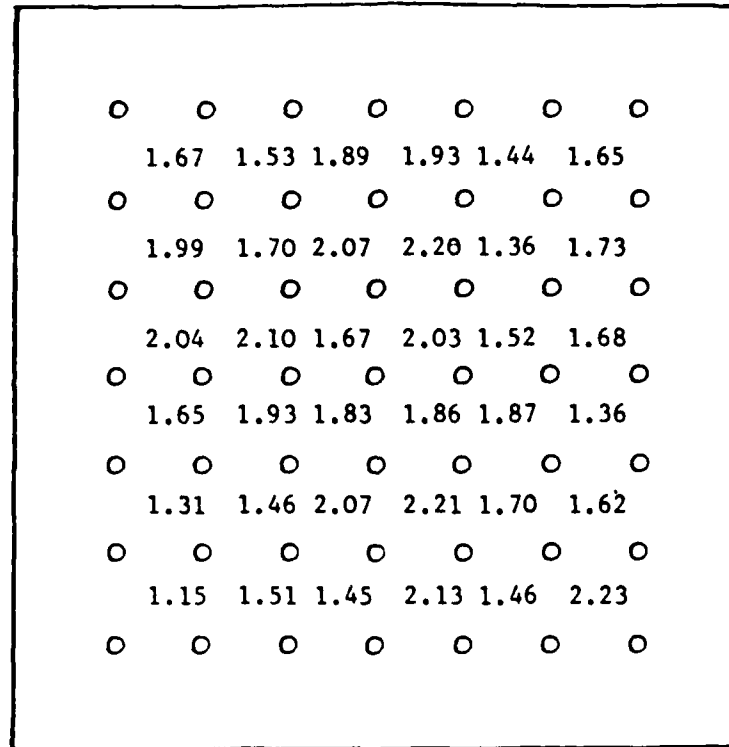
Average ϵ_1 (area 2) = 1.71% with standard deviation 0.37%

Average ϵ_1 (area 3) = 2.00% with standard deviation 0.34%

Monotonic shear loading at stress ratio 6 (1st loading) photography

Figure 9d (after Wong & Arthur (4))

σ_1



Average ϵ_1 (area 1) = 1.75% with standard deviation 0.29%

Average ϵ_1 (area 2) = 1.85% with standard deviation 0.26%

Average ϵ_1 (area 3) = 1.85% with standard deviation 0.15%

Monotonic shear loading at stress ratio 6 (1st Loading), radiography

Figure 9e (after Wong & Arthur (4))

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